

Mixed-dimension silver nanowires for solution-processed, flexible, transparent and conducting electrodes with improved optical and physical properties

Kumar, Dinesh; Stoichkov, Vasil; Ghosh, Sanjay; Smith, G. C.; Kettle, Jeffrey

Flexible and Printed Electronics

DOI:

[10.1088/2058-8585/aa6011](https://doi.org/10.1088/2058-8585/aa6011)

Published: 20/03/2017

Peer reviewed version

[Cyswllt i'r cyhoeddiad / Link to publication](#)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):

Kumar, D., Stoichkov, V., Ghosh, S., Smith, G. C., & Kettle, J. (2017). Mixed-dimension silver nanowires for solution-processed, flexible, transparent and conducting electrodes with improved optical and physical properties. *Flexible and Printed Electronics*, 2(1), [015005].
<https://doi.org/10.1088/2058-8585/aa6011>

Hawliau Cyffredinol / General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Mixed dimensions silver nanowires for solution processed, flexible, transparent and conducting electrodes with improved optical and physical properties

D. Kumar¹, V. Stoichkov¹, S. Ghosh¹, G.C. Smith², J. Kettle^{1*}

¹ Bangor University, School of Electronic Engineering, Dean Street, Bangor, UK, LL57 1UT

² Department of Natural Sciences, University of Chester, Thornton Science Park, Chester, CH2 4NU, UK

Abstract. In this work, we present an alternative method for the spray coating of silver nanowires contact electrodes by employing a mixture of short and long nanowires. Mixed silver nanowires are found to give improve optical properties with 2-5% higher transparency for the same sheet resistance of $25 \Omega\text{sq}^{-1}$, when compared to silver nanowires prepared with a single geometry nanowire. The figure of merit (FoM) for the $25 \Omega\text{sq}^{-1}$ sheet resistance electrode was found to be highest for the mixed composition AgNWs-M1 (mixture of AgNWs-30L and AgNWs-60S) based electrodes. Furthermore, the average root mean square surface roughness (R_q) parameter by white light interferometry (WLI) are found to be lower for the mixed composition silver nanowires electrodes ($R_q = 3\text{-}4 \text{ nm}$) when compare to the individual parent fixed dimension type silver nanowire electrodes ($R_q = 6\text{-}8 \text{ nm}$).

Keywords: silver nanowires, transparent conducting electrodes, surface roughness

*Author, E-mail: j.kettle@bangor.ac.uk

1 Introduction

Transparent conducting electrodes (TCEs) are an essential component of many electronic devices such as organic photovoltaic (OPV), electronic displays, wearable devices, transparent heaters and touch screens.¹⁻³ Indium tin oxide (ITO) based TCEs are most widely used by industry and have dominated the field of photo electronic applications for the last several decades. However, due to potential future increase in ITO cost and owing to the poor stability upon bending, a search for

new materials to replace ITO is a hot current research topic for both the academic and industrial communities. The potential replacements for ITO includes conducting polymer,⁴ graphene,⁵ carbon nanotubes,⁶⁻¹⁰ copper nanowires^{11,12} and silver nanowires (AgNWs).^{2,13-15} Among these materials, AgNW based TCEs have emerged as the lead alternative because of properties such as high transparency and low sheet resistance (R_{sh}) close to or even better than those with ITO^{2,14} An advantage of silver nanowires is the simple method of their synthesis with tailor made dimensions especially by the polyol process.^{16,17} Moreover, AgNW based TCEs can be made highly flexible, relatively less expensive and are compatible with a roll-to-roll manufacturing process.¹⁸ The general requirements for transparent conducting electrodes consists of low R_{sh} , typically less than $100 \Omega \text{ sq}^{-1}$ whilst maintaining high transparency (above 90% in the visible region of the spectrum.)^{19,20} The requirement also varies with the type of application, for instance, solar cell application required optimum optical haze whereas for display application, a low haze factor is important. Optical/electrical properties of silver nanowires based transparent electrodes depends on a number of factors including types of AgNWs,¹⁴ deposition process³ and post treatment of samples such as mechanical pressing^{21,22} fast sintering²³ and thermal annealing²⁴. Typical dimensions of silver nanowires are of mean diameter (d_{mean}) of 30-200 nm and mean length (l_{mean}) of 20-400 μm . There are a number of studies in the literature of the physical properties of transparent electrodes prepared by utilizing particular types of silver nanowires, for examples, silver nanowires with dimensions of nanowires of either thinner or thicker mean diameter¹⁴ and/or shorter or longer mean length.²⁶ Currently, the best performance was obtained by Preston et al, who reported $13 \Omega \text{ sq}^{-1}$ with 91% transparency in the visible region using post-processing^x. The best performance achieved without post-processing was achieved by Andrés et al who used spray coating of ultra-long nanowires to achieve $13 \Omega \text{ sq}^{-1}$ having 91%¹⁴. Despite this impressive

performance, the RMS roughness, R_q , of the samples was measured at 14nm and maximum peak to valley, P.V. (nm) was measured at 90nm, which is typical for AgNW films.

Dinesh – add the references where I placed X

<http://pubs.rsc.org/en/content/articlelanding/2014/tc/c3tc31726a#!divAbstract>

Table is deleted, so please update the numbers

In this work, we focus our attention on the physical properties of electrodes prepared by using a mixed composition of two different geometries of silver nanowires. The mixed silver nanowires were used as a precursor dispersion in the solvent (ethanol) for coating flexible transparent substrates by employing the simple and cost effective air spray coating technique.

Three types of silver nanowires were used for the study namely *thin-short* nanowire; AgNWs-60S ($d_{mean} = 60$ nm, $l_{mean} = 20-30$ μ m), *thin-long* nanowire; AgNWs-30L ($d_{mean} = 30$ nm, $l_{mean} = 100-200$ μ m) and *thick-long* nanowires; AgNWs-100L ($d_{mean} = 100$ nm, $l_{mean} = 100-200$ μ m). The shorter nanowires are advantageous for achieving high conducting networks at low concentration and the longer nanowires provide higher conductivity performance. The combined advantages of short and long nanowire were exploited by coating them together. Two mixed silver nanowires composition were prepared, one consisted of the type: *thin-short* nanowires (AgNws-60S) with *thin-long* nanowires (AgNWs-30L), denoted as ‘AgNWs-M1’, and another one consist of the type: *thin-short* nanowires (AgNWs-60S) with *thick-long* nanowires (AgNWs-100L), denoted as AgNWs-M2. The results show a moderate improvement in the electrical/optical performance and in the surface roughness.

2 Experimental

2.1 Materials

Silver nanowires of the type AgNWs-60S, AgNWs-30L and AgNWs-100L (silver purity 99.5%, concentration 20 mg/mL in ethanol) were purchased from ACS materials. All materials were diluted with ethanol to the concentration of 0.5 mg/mL prior to spray coating. Flexible transparent substrates of planarised polyethylene-naphthalate (PEN) with thickness 125 μm were used for this work. PEN was spin coated with poly methyl methacrylate (PMMA) (molecular weight 495K, 8% solution in anisole) purchased from Microchem. For this work, a PMMA buffer layer was employed to reduce the surface roughness of the substrates. HPLC grade isopropyl alcohol (IPA), ethanol (EtOH) and acetone were purchased from Sigma-Aldrich and used as such.

2.2 AgNW film preparation

Mixed composite silver nanowires AgNWs-M1 dispersion was prepared by mixing AgNW-60S and AgNWs-30L as supplied in 1:1 volume by volume (V/V) ratios and then diluted with ethanol to 0.5 mg/mL final concentration. After some initial tests, the ratio of 1:1 was found to be the optimum, so all benchmarking of performances were done at this ratio. Similarly, AgNWs-M2 was prepared with AgNWs-60S and AgNWs-100L. Silver nanowires dispersions in ethanol of each type (0.5 mg/mL) were sonicated for 5 minutes to minimize aggregates before air spray coating. Ultrasonication was used prior to spray coating to ensure that the AgNWs were dispersed in the suspension prior to spray coating. A short duration was used (<5 minutes) at low power in order to ensure no breakage of AgNWs. For air spray coating, a back pressure of air kept at 1 bar using a piston type oil-less airbrush compressor was used for uniform gas/liquid flow rate (0.2 ml/min) at the nozzle. The spray nozzle diameter was 0.5 mm and the fluid cup capacity was

7 cm⁻³ with the air compressor. Substrates PEN of area 15 mm × 18 mm were thoroughly cleaned with DI water, acetone and IPA followed by drying with a jet flow of nitrogen. PMMA was spin coated on cleaned PEN substrates at 2500 rpm for 20 seconds followed by annealed at 100 °C for one minute. The substrates were placed on the substrate heater at 60 °C and the silver nanowires dispersion was air sprayed onto the heated substrates to evaporate the EtOH. The deposition time for preparing electrodes with $R_{sh} \approx 25 \Omega \text{ sq}^{-1}$ was found to be approximately 5 mins ±30 seconds. However, using mixed geometry electrodes, the deposition time was approximately 50% lower. This represents a significant advantage for future scale up of the technology.

2.3 Physical properties characterization

Transmittance spectra of silver nanowire- polymer composite electrode were recorded in the region 350 nm to 1000 nm with PEN as reference using HR4000CG-UV-NIR high resolution spectrometer (Ocean optics, Inc. USA). Sheet resistance (R_{sh}) was measured by four probe setup (A & M. FELL Ltd., England). Surface roughness was estimated by white light interferometer measurement (WLI) using Micro XAM surface mapping microscope (KLA tensor, USA). Scanning electron microscopes (SEM) images were obtained using a Leo 1455VP SEM operating at 30 kV with 10 pA beam current at typical magnifications of x10,000.

3 Results and Discussion

Fig.1a depicts a schematic diagram for the preparation of the silver nanowires-polymer composite TCEs technique developed in this work. PMMA was spin coated on PEN followed by annealing at 100 °C for 1 min to give about 10 µm thick planarization layer. After cooling, the substrate was

placed on hot plate at 60 °C onto which silver nanowire dispersion was spray coated to produce the TCE.

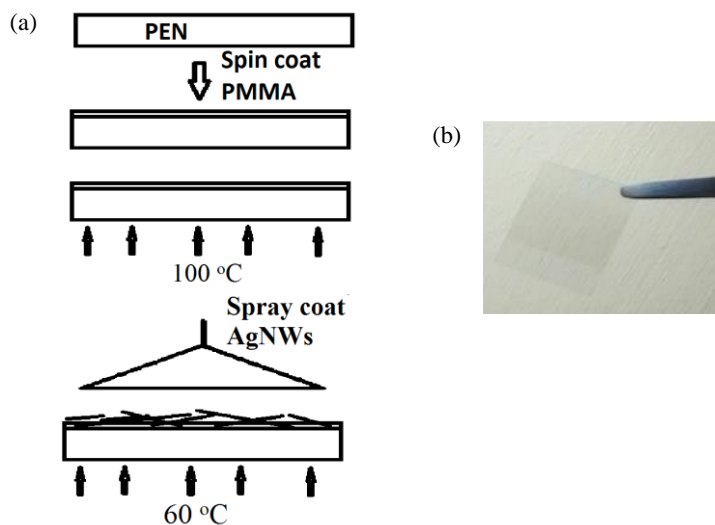


Fig. 1 a) Schematic diagram of spray coat technique for a silver nanowires-polymer composite electrode preparation b) Image of spray coated silver nanowire on PMMA coated PEN substrate based TCE develop in this work.

For illustration, a sample silver nanowire TCE prepared is showed in **fig. 1b**, displaying the conducting surface area of 12 mm x 15 mm on the substrate.

SEM images of the conducting surface of silver nanowires electrodes prepared from fixed dimension type silver nanowires AgNWs-30L and AgNWs-60S is shown in **fig. 2a** and **fig. 2b** while a mixed composition type AgNWs-M2 is shown in **fig. 2c**. The inter mixing of *short-thin* nanowires AgNWs-60S with *long-thick* nanowires AgNWs-100L can be clearly seen from **fig.2c**, which provides more event surface coverage and as a result of fewer aggregations at nanowire junctions.

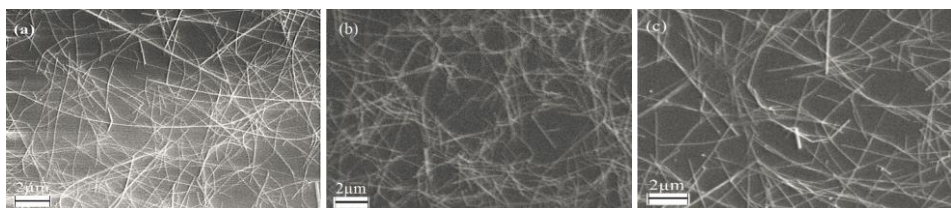


Fig. 2 SEM images of a) AgNWs-30L b) AgNWs-60, c) AgNWs-M2. The scale bar indicates 2μm

3.1 Optical properties

The transmittance spectra of TCE prepared by the different type silver nanowires dispersion with a similar R_{Sh} of $25 \pm 1 \Omega \text{ sq}^{-1}$ are represented in **fig. 3**. This value of R_{Sh} was chosen as it represents a sizeable improvement over ITO on a flexible substrate and is comparable to the value of ITO often used on glass substrates. It has been reported in the literature that for a given R_{Sh} , longer silver nanowires have greater transmittance than shorter nanowires and also, to some extent, thicker nanowires greater than thinner ones.^{14, 26, 28} It can be seen from **fig. 3** that longer silver nanowires electrodes (AgNWs-100L, AgNWs-30L) shows 5-10% transmittance improvement in the visible region of spectrum compare to the shorter nanowires AgNWs-60S. In addition, the *thin-long* nanowires (AgWS-30L) electrode was found to show higher transmittance than the *thick-long* nanowires (AgNWs-100L) electrode with same R_{Sh} of $25 \Omega \text{ sq}^{-1}$ (**Fig. 3**). The mixed composition silver nanowires AgNWs-M1 electrode shows similar overall transmittance values to the longer nanowire component AgNWs-30L, but with moderate improvement in the region 400 nm to 550 nm of visible spectrum. This could be a significant result for academics and industrialists working with blue OLEDs, who wish to maximize the light output in this region. Likewise, the AgNWs-M2 electrode displayed better transmittance compared to its parent silver nanowires

electrodes of AgNWs-60S and AgNWs-100L and improved performance in the blue-green spectrum.

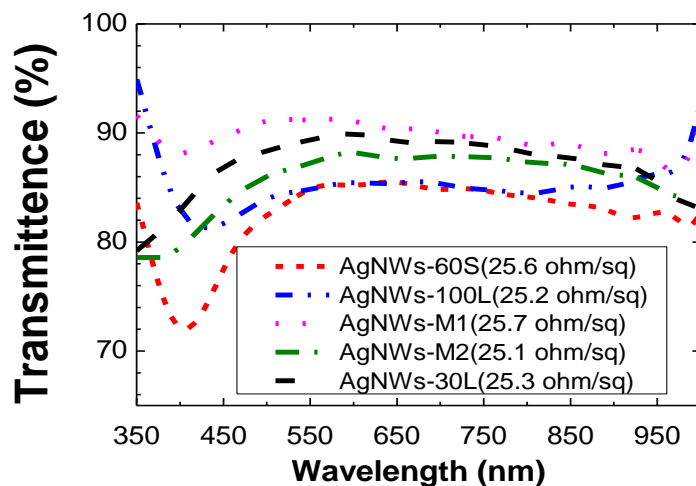


Fig. 3 Transmittance spectra of AgNWs-30L, AgNWs-60S, AgNWs-100L, AgNWs-M1 and AgNWs-M2 composite electrodes with sheet resistance of $25 \Omega \text{ sq}^{-1}$

Due to the reduced aggregation and better percolation of the mixed AgNW films, the transparency is greater for the same sheet resistance. Due to the reduced aggregation and better percolation, the overall silver content of the film is lower. For the samples shown in table 2, the silver content is calculated at 2 mg/cm^2 is for mixed, which compares to 3 mg/cm^2 four long AgNWs and for 4 mg/cm^2 short AgNWs.

Commented [L1]: Estimate to 1 or 2 decimal points

Table 2. Silver content for mixed (AgNWs-M1), long (AgNWs-30L) and short (AgNWs-60S) electrodes

AgNWs type	Silver content (mg/cm ⁻²)
Mixed	0.20
Long	0.31
Short	0.42

Commented [L2]: Can you add 2 decimal points

To quantify the optical and electrical properties a figure of merit (FoM) is commonly defined by the community given in equation (2), where R_{Sh} is the sheet resistance and T is the transmittance.²⁹

$$FoM = \frac{188.5}{R_{sh}(\sqrt{1/T} - 1)} \quad (2)$$

One of the highest FoM value reported in literature is 338 for silver nanowires electrodes with a R_{Sh} of 20 Ω sq⁻¹ electrodes and transparency at 550 nm of 94.7%, prepared by spray deposition of silver nanowires.¹⁴ By comparison, for commercial ITO films on PET used in our laboratory, the FoM is around 58 (R_{Sh} = 60 Ω sq⁻¹, transparency = 90%, source Sigma Aldrich, UK).

Type	R_{sh} (Ω sq ⁻¹) (Best)	R_{sh} (Ω sq ⁻¹) (Average)	R_{sh} (Ω sq ⁻¹) (STDV)	T (%) (Best)	T (%) (Average)	T (%) (STDV)	FoM (Best)	FoM (Average)	Haze (%)
AgNWs-M1	25.7	25.9	0.2	90.2	89.8	0.5	138.6	131.6	0.8
AgNWs-M2	25.1	25.4	0.4	87.1	86.4	0.9	105.0	97.8	0.9

AgNWs-60S	25.6	26.0	0.8	84.7	84.1	0.4	85.1	80.1	1.1
AgNWs-30L	25.3	25.8	0.7	89.3	88.8	0.6	127.9	119.4	0.6
AgNWs-100L	25.2	25.4	0.3	84.8	84.0	1.0	87.0	81.4	1.0

Table 3. Average (from 5), best and standard deviation of sheet resistance and transmittance of (AgNWs-M2), short (AgNWs-60S) and long (AgNWs-30L) electrodes

The FoM values calculated for various silver nanowires electrodes of $25 \Omega \text{ sq}^{-1}$ R_{sh} with transmittance (%T) at 550 nm is plotted in **fig. 4**. Among the different silver nanowire type electrodes studied, the mixed composition silver nanowires electrodes AgNWs-M1 (FoM = 138.6, Fig. 4) has the highest FoM value while lowest for *short-thin* nanowires AgNWs-60S (FoM = 85.1, Fig. 4). Mixed composition silver nanowires electrodes (AgNWs-M1, AgNWs-M2) optical performance in terms of FoM is found higher compare to the parent silver nanowires electrodes (AgNWs-30L, AgNWs-60S, AgNWs-100L) R_{sh} of $25 \Omega \text{ sq}^{-1}$. In table 3, the best and average performances of the three most promising combinations are shown i.e. (**AgNWs-M2**), **short (AgNWs-60S)** and **long (AgNWs-30L)**. When considering the FoM, the mixed AgNW films show around 10-15% improvement over the best obtained results from an AgNW film prepared from a single nanowire geometry (**AgNWs-30L**). In addition, the mixed AgNW film shows 30-40% improvement over AgNW films prepared with short nanowires. The results support the conclusion that short nanowires do not provide good percolating networks and therefore exhibit poorer performance than longer nanowires. However, they could still have industrial applications, should they be used in combination with longer nanowires.

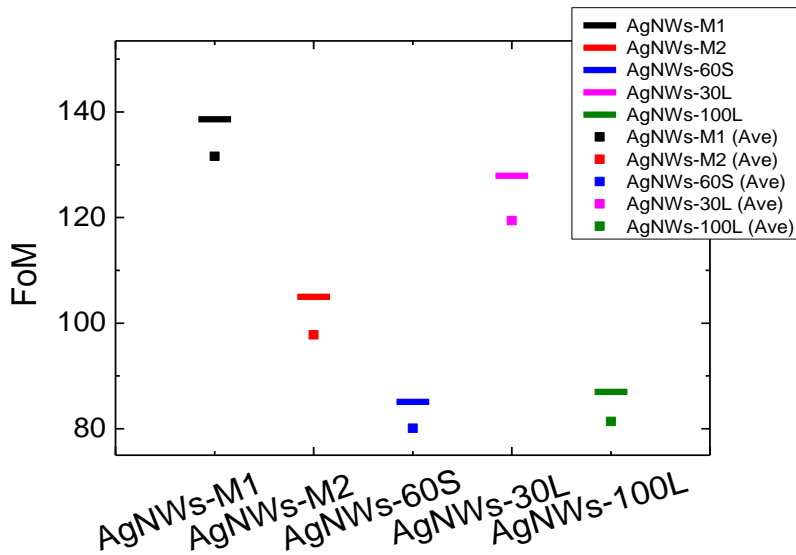


Fig.4 Best and average figure of merit (FoM) of silver nanowires electrodes with sheet resistance of $25 \Omega\text{sq}^{-1}$.

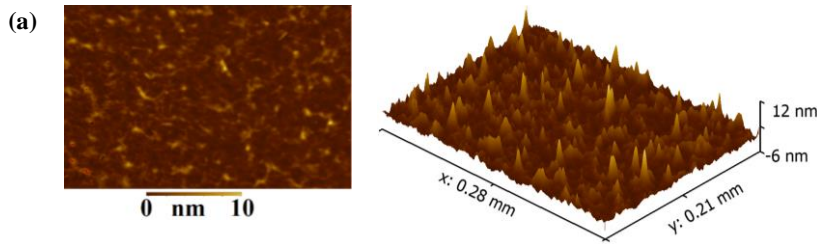
3.2 Roughness

The surface roughness of the conductive surface of the AgNW electrodes was examined by white light interferometry (WLI). **Fig.5** shows the topological images of AgNWs-30L, AgNWs-60S and AgNWs-M2 electrodes, respectively. The surface roughness is an important factor for optimum performance of thin-film electronic devices such as OLEDs and OPVs. These devices tend to have thin interlayers and active layers and high surface roughness can lead to electrical shorts between the anode and cathode. One disadvantage of metallic nanowire electrodes has been the high surface roughness, which is primarily due to junctions formed where two or more nanowires are stacked on top of one another, creating large local height spikes. As a result of the local height spikes, the peak-to-valley (PV) values can reach up to three times the value of the diameter of the

nanowires.^{22,30,31} This effect is more pronounced when metallic nanowires are deposited on rigid surfaces such as glass, for instance, peak-to-valley value above 500 nm as determined by atomic force microscopic (AFM) measurements.³⁰ In order to reduce the surface roughness of silver nanowires electrode several approaches has been reported including mechanical pressing^{22,32-34} and peel off using cross linked polymers.²⁵⁻²⁷

Table 4 shows the surface roughness of various types of nanowires electrodes, (AgNW-30L, AgNW-60S, AgNWs-100L, AgNWs-M1, AgNWs-M2) by WLI measurement over large area of 278 μm x 207 μm . In this work, the surface roughness was calculated from an average of five different samples and the average root mean square roughness (R_q) and maximum peak-to-valley (P-V) roughness was calculated.

For all samples, the highest average P-V roughness was obtained for the short nanowires (PV = 87.2nm), although the surface roughness is overall much lower than other reports. The low peak-to-valley roughness was attributed to the PMMA layer, which possibly facilitate the embedding of nanowires, thereby smoothening the surface.



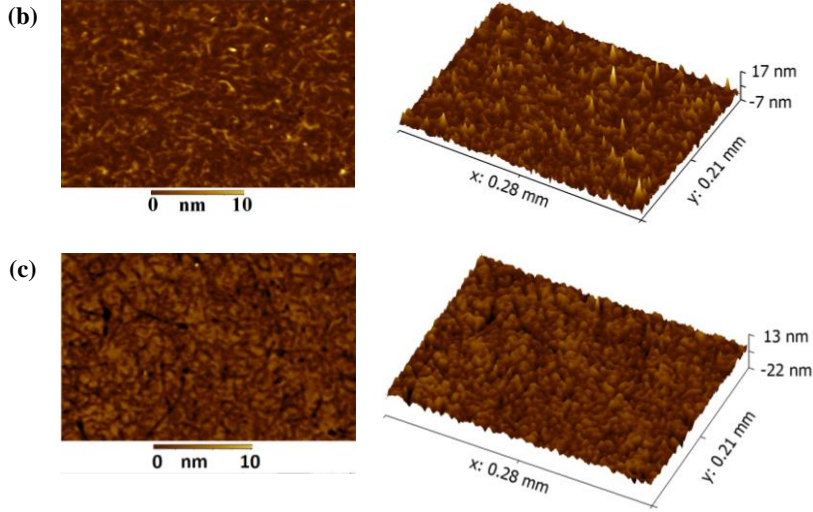


Fig.5 WLI topological images of a) AgNWs-60S, b) AgNWs-30L c) AgNWs-M2 on PMMA coated PEN.

The root mean square roughness (R_q) for the mixed composition silver nanowires electrodes (AgNWs-M1, AgNWs-M2) are found in the range 3-4 nm while for the fixed dimension type nanowires electrodes (AgNWs-30L, AgNWs-60S, AgNW-100L) the values are in the range 6-8 nm. This indicates that the mixed composition silver nanowires electrodes possess a somewhat smoother surface compare to the fixed dimension type silver nanowires electrodes, attributed due to a more evenly distributed surface coverage (see figure 2). For illustration, topological images of a short, a long and a mixed composition type nanowires electrodes are shown in **fig. 5**. It can be seen by visual inspection of fig.5 that AgNWs-M2 ($R_q = 3.7$ nm, $PV = 79.6$ nm), based electrodes topological image is smoother compare to AgNWs-30L ($R_q = 5.5$ nm, $PV = 77.3$ nm) and AgNW-60S ($R_q = 7.9$ nm, $PV = 81.7$ nm) electrodes. **The high surface roughness of AgNWs is a result of**

multiple AgNWs overlapping upon one another, or by aggregation of multiple nanowires. The procedure developed in this paper involves depositing the long AgNWs initially. A low volume of material is used during this deposition, so the long AgNWs are dispersed quite evenly across a sample and the amount of overlap is relatively low. Long AgNWs tend to form more aggregates during the spray coating deposition, so by minimising the volume deposited, the concentration of aggregates are reduced, thus reducing the overall surface roughness. Subsequently the short AgNWs are deposited. Short AgNWs do not tend to form large aggregates. Therefore, these act as an ‘in-fill’ into the long AgNW mesh, providing the percolation and ensuring no major aggregation points are formed.

Table 4. Surface roughness parameters of mixed (AgNWs-M2), short (AgNWs-60S) and long (AgNWs-30L) electrodes

Type	Rq (nm) average	Rq (nm) STDV	Pv (nm) average	Pv (nm) STDV
AgNWs-M1	3.2	0.2	75.2	2.1
AgNWs-M2	4.1	0.4	80.9	2.9
AgNWs-60S	8.5	1.2	87.2	3.9
AgNWs-30L	6.2	0.6	85.9	3.8

AgNWs- 100L	5.9	0.3	80.1	2.0
------------------------	-----	-----	------	-----

4. Conclusions

We have demonstrated an alternative approach for spray coating AgNW electrodes onto flexible substrates by employing AgNW with mixed geometries. The advantage of mixed composition silver nanowires, comprising of short nanowires length ($l_{mean} = 25 \mu\text{m}$) with long nanowire ($l_{mean} = 150 \mu\text{m}$), include shorter spray coat deposition time, better electrical/optical properties (as evidenced by the FoM values) and lower surface roughness electrodes. We believe that the simple technique demonstrated in this work will be effective in saving time and cost for large-scale production of silver nanowires based transparent conducting electrodes and helpful for further development of metallic nanowires based electrodes in general. One combination which has not been investigated in this paper is the combination of AgNWs60S, AgNWs30L and AgNWs100L. This could provide an alternative strategy for improving the performance further. However, the preparation time will increase by ~60%, due to the application of an additional long AgNW layer, which is unlikely to be suitable for large-scale production of AgNW films.

Acknowledgments

This work was supported by the “UK Engineering and Physical Sciences Research Council through the EPSRC Centre for Innovative Manufacturing in Large Area Electronics (grant number EP/K03099X/1).” Vasil Stoichkov would like to thank Sêr Cymru National Research Network for funding of his PhD studies. We would like to thank Dr David Gomez, Maria Fernandez and others at Fundacion ITMA, Aviles, Asturias, Spain for their kind support and initial help with spray coating nanowires.

References

1. M. Layani, A. Kamyshny and S. Magdassi, “Transparent conductors composed of nanomaterials,” *Nanoscale* **6**, 5581–5591 (2014). [doi: 10.1039/c4nr00102h]
2. D. Langley, G. Giusti, C. Mayousse, C. Celle, D. Bellet and J. P. Simonato, “Flexible transparent conductive materials based on silver nanowire networks: a review,” *Nanotechnology* **24**(45), 452001 (2013) [doi:10.1088/0957-4484/24/45/452001].
3. C. F. Guo and Z. Ren, “Flexible transparent conductors based on metal nanowire networks,” *Mater. Today*, **18**(3), 143–154 (2015) [doi: 10.1016/j.mattod.2014.08.018].
4. S. Ye, R. Rathmell, Z. Chen, I. E. Stewart and B. J. Wiley, “Metal nanowire networks: The next generation of transparent conductors,” *Adv. Mater.* **26**(39), 6670–6687 (2014) [doi: 10.1002/adma.201402710].

5. S. Pang, Y. Hernandez, X. Feng and K. Müllen, “Graphene as transparent electrode material for organic electronics,” *Adv. Mater.* **23**(25), 2779–2795 (2011) [doi: 10.1002/adma.201100304].
6. B. Dan, G. C. Irvin, M. Pasquali, B. Dan, G. C. Irvin and M. Pasquali, “Continuous and Scalable Fabrication of Nanotube Films,” *ACS Nano* **3**(4), 835–843 (2009) [doi: 10.1021/nn8008307 CCC].
7. D. S. Hecht, A. M. Heintz, R. Lee, L. Hu, B. Moore, C. Cucksey and S. Risser, “High conductivity transparent carbon nanotube films deposited from superacid,” *Nanotechnology*, **22**(7), 75201 (2011) [doi:10.1088/0957-4484/22/7/075201].
8. H. Wu, L. Hu, T. Carney, Z. Ruan, D. Kong, Z. Yu, Y. Yao, J. J. Cha, J. Zhu, S. Fan and Y. Cui, “Low reflectivity and high flexibility of tin-doped indium oxide nanofiber transparent electrodes,” *J. Am. Chem. Soc.* **133**(1), 27–29 (2011) [doi:10.1021/ja109228e].
9. N. Ferrer-Anglada, J. Pérez-Puigdemont, J. Figueras, M. Z. Iqbal and S. Roth, “Flexible, transparent electrodes using carbon nanotubes,” *Nanoscale Res. Lett.* **7**(1), 571 (2012) [http://www.nanoscalereslett.com/content/7/1/571].
10. A. E. Ostfeld, A. Catheline, K. Ligsay, K. Kim, Z. Chen, A. Facchetti, S. Fogden and A. C. Arias, “Single-walled carbon nanotube transparent conductive films fabricated by reductive dissolution and spray coating for organic photovoltaics single-walled carbon nanotube transparent conductive films fabricated by reductive dissolution and spray coating for organic photovoltaics,” *App. Phys. Lett.* **105**, 253301 (2014) [doi: 10.1063/1.4904940].
11. A. R. Rathmell and B. J. Wiley, “The synthesis and coating of long, thin copper nanowires to make flexible, transparent conducting films on plastic substrates,” *Adv. Mater.* **23**(41), 4798–4803 (2011) [doi: 10.1002/adma.201102284].

12. F. Cui, Y. Yu, L. Dou, J. Sun, Q. Yang, C. Schildknecht, K. Schierle-Arndt and P. Yang, "Synthesis of Ultrathin Copper Nanowires Using Tris(trimethylsilyl)silane for High-Performance and Low-Haze Transparent Conductors," *Nano Lett.* **15**(11), 7610–7615 (2015) [doi: 10.1021/acs.nanolett.5b03422].
13. L. Hu, H. S. Kim, J. Y. Lee, P. Peumans and Y. Cui, "Scalable coating and properties of transparent, flexible, silver nanowire electrodes," *ACS Nano* **4**(5), 2955–2963 (2010) [doi: 10.1021/nn1005232].
14. L. José Andrés, M. Fe Menéndez, D. Gómez, A. Luisa Martínez, N. Bristow, J. Paul Kettle, A. Menéndez and B. Ruiz, "Rapid synthesis of ultra-long silver nanowires for tailor-made transparent conductive electrodes: proof of concept in organic solar cells.," *Nanotechnology*, **26**, 265201 (2015) [doi:10.1088/0957-4484/26/26/265201].
15. G. A. Benatto, B. Roth, M. Corazza, R. R. Søndergaard, S. A. Gevorgyan, M. Jørgensen and F. C. Krebs, "stability of flexible ITO-free organic solar cell modules," *Nanoscale*, **8**(1), 318–326 (2016) [doi: 10.1039/c5nr07426f].
16. Y. Sun, "Silver nanowires – unique templates for functional nanostructures," *Nanoscale*, **2**(9), 1626–1642 (2010) [doi: 10.1039/c0nr00258e].
17. Y. Sun, B. Mayers, T. Herricks and Y. Xia, "Polyol Synthesis of Uniform Silver Nanowires: A Plausible Growth Mechanism and the Supporting Evidence," *Nano Lett.* **3**(7), 955–960 (2003) [doi: 10.1021/nl034312m CCC]
18. D. Angmo, T. R. Andersen, J. J. Bentzen, M. Helgesen, R. R. Søndergaard, M. Jørgensen, J. E. Carlé, E. Bundgaard and F. C. Krebs, "Roll-to-Roll Printed Silver Nanowire Semitransparent Electrodes for Fully Ambient Solution-Processed Tandem Polymer Solar Cells," *Adv. Funct. Mater.* **25**(28), 4539–4547 (2015) [doi: 10.1002/adfm.201501887].

19. K. Ellmer, “Past achievements and future challenges in the development of optically transparent electrodes,” *Nat. Photonics* **6**(12), 808–816 (2012) [doi:10.1038/nphoton.2012.282].
20. C. Celle, C. Mayousse, E. Moreau, H. Basti, and A. Carella, “Highly Flexible Transparent Film Heaters Based on Random Networks of Silver Nanowires,” *Nano Res.* **5**(6), 427–433 2012. [doi 10.1007/s12274-012-0225-2]
21. X. Y. Zeng, Q. K. Zhang, R. M. Yu, and C. Z. Lu, “A new transparent conductor: Silver nanowire film buried at the surface of a transparent polymer,” *Adv. Mater.* **22**(40), 4484–4488 (2010).
22. H. H. Khaligh and I. A. Goldthorpe, “Hot-rolling nanowire transparent electrodes for surface roughness minimization,” **9**, 310 (2014) [<http://www.nanoscalereslett.com/content/9/1/310>]
23. J. Jiu, T. Sugahara, M. Nogi, T. Araki, K. Suganuma, H. Uchida and K. Shinozaki, “High-intensity pulse light sintering of silver nanowire transparent films on polymer substrates: the effect of the thermal properties of substrates on the performance of silver films,” *Nanoscale* **5**, 11820–11828, 2013 [doi: 10.1039/c3nr03152g].
24. D. P. Langley, M. Lagrange, G. Giusti, C. Jiménez, Y. Bréchet, N. D. Nguyen and D. Bellet, “Metallic nanowire networks: effects of thermal annealing on electrical resistance.,” *Nanoscale*, **6**(22), 13535–13543 (2014) [doi: 10.1039/c4nr04151h].
25. Z. Yu, X. Niu, Z. Liu and Q. Pei, “Intrinsically stretchable polymer light-emitting devices using carbon nanotube-polymer composite electrodes,” *Adv. Mater.* **23**(34), 3989–3994 (2011) [doi:10.1002/adma.201101986].

26. Z. Yu, L. Li, Q. Zhang, W. Hu and Q. Pei, “Silver nanowire-polymer composite electrodes for efficient polymer solar cells,” *Adv. Mater.* **23**(38), 4453–4457 (2011) [doi: 10.1002/adma.201101992]
27. Y. S. Liu, J. Feng, X. L. Ou, H. F. Cui, M. Xu and H. B. Sun, “Ultrasmooth, highly conductive and transparent PEDOT:PSS/silver nanowire composite electrode for flexible organic light-emitting devices,” *Org. Electron.* **31**, 247–252 (2016) [doi: 10.1016/j.orgel.2016.01.014].
28. M. Lagrange, D. P. Langley, G. Giusti, C. Jiménez, Y. Bréchet, and D. Bellet, “Optimization of silver nanowire-based transparent electrodes: effects of density, size and thermal annealing,” *Nanoscale*. **7**(41), 17410–17423 (2015) [doi: 10.1039/c5nr04084a].
29. S.B. Sepulveda-Mora and S.G Cloutier, “Figures of merit for high-performance transparent electrodes using dipcoated silver nanowire networks,” *J. Nanomater.* 9–15 (2012). [doi:10.1155/2012/286104]
30. Z. Yu ,Q. Zhang,L. Li,Q. Chen, X. Niu, J. Liu, Q. Pei “Highly flexible silver nanowire electrodes for shape-memory polymer light-emitting diodes,” *Adv Mater.* **23**,664–668(2011).
31. D. Y. Choi, H. W Kang,H. J. Sung, S. S Kim “Annealing-free, flexible silver nanowire-polymer composite electrodes via a continuous two-step spray-coating method”. *Nanoscale* **5**:977–983 (2013).
32. B. X. Zeng, Q. Zhang, R. Yu, and C. Lu, “A New Transparent Conductor : Silver Nanowire Film Buried at the Surface of a Transparent Polymer,” *Adv. Mater.* **22**, 4484–4488 (2010) [doi: 10.1002/adma.201001811]

33. S. Nanowire, L. Hu, H. S. Kim, J. Lee, P. Peumans, and Y. Cui, “Scalable Coating and Properties of Transparent, Flexible, Silver Nanowire Electrodes,” *ACS Nano* **4**(5), 2955–2963 (2010) [doi: 10.1021/nn1005232].
34. T. C. Hauger, S. M. I. Al-Rafia and J. M. Buriak, “Rolling Silver Nanowire Electrodes : Simultaneously Addressing Adhesion, Roughness, and Conductivity,” *ACS App. Mater. Interfaces* **5**, 12663–12671 (2013).[doi:10.1021/am403986f].
35. Z. Ding, V. Stoichkov, M. Horie, E. Brousseau, E. and J. Kettle, “Spray coated silver nanowires as transparent electrodes in OPVs for Building Integrated Photovoltaics applications.” *Solar Energy Materials and Solar Cells*, 157, pp.305-311. (2016)